Notes

Agricultural Runoff as a Nonpoint Externality: A Theoretical Development

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The purpose of this paper is to develop and explore a theory dealing with an important facet of agricultural runoff problems. Agricultural runoff is a nonpoint externality with notable implications for both research and policy. A nonpoint externality exists whenever the externality contributions of individual economic agents cannot be practically measured by direct monitoring. Without monitoring, regulations on emissions cannot be enforced, and charges or subsidies cannot be assessed. Thus, policies which are usually suggested for pollution abatement are not available. There is great need for a theoretical base that can adequately capture these facts. Such a theory yields some important implications even before specific empirical applications.

The economic problem of agricultural runoff can be separated into three distinct categories. First, the sediment, nutrients, and chemicals removed by runoff represent a loss of resources to the individual farmer. These costs are borne privately by farmers.

Second, if the discount rate of the individual farmer is greater than the social discount rate, or if the farmer has a planning horizon which is shorter than society's, the farmer will mine the soil resource at a rate which is more depletive than is socially optimal. This is a temporal externality.

A third category involves the conservation of mass. Physical resources lost by the individual farm must appear elsewhere in the environment. In sufficient quantities, these resources are pollutants. Since water is the primary transport media for these resources, it is water that is polluted by soil, nutrients, and agricultural chemicals. This spatial externality has been the focus of much research. Here we intend to develop a theory for these issues, to employ it to suggest a revised research methodology, and to provide some important conclusions about alternative runoff policies.

Only two of the three categories of agricultural runoff problems involve externalities, and only the spatial externality is considered here.

A Theory of Nonpoint Externalities

The purpose of this section is to develop a nonpoint externality theory. Economically efficient regulatory and incentive policies will be devised and their optimal parameters mathematically specified. The development begins with a simple static model of the traditional point-source externality.

A Point Externality

In this single-period model we assume that it is either impossible or too costly to determine consumers' valuations of marginal benefits from reducing emissions of a point-source pollutant. Instead, we assume that a regional limit on emissions has been politically or bureaucratically resolved and that the objective is to achieve this goal at least cost to the region.

Starting from the Baumol and Oates framework for modeling depletable and detrimental externalities in a least-cost setting, let $\mathbf{y}^j$ be the production bundle of firm j with y_n^j being the nth element (positive or negative) of that vector. Positive activities represent outputs; negative ones are inputs. There are J firms. Excluding the pollutant, there are N goods or activities. Pollutant emissions by firm j are nonnegative and are denoted z^j. Total pollutant emissions summed across all firms are limited to Z^*.

Production relationships are allowed to differ among firms. Firm j's production set is given implicitly by $f^j(\mathbf{y}^j, z^j) \leq 0$, although it is assumed that each firm fully exploits its productive abilities. Consequently, these relationships become equalities.

Given this specification, society's problem can be formalized as a desire to maximize total profits given productive abilities and the constraint on emissions. Society's Lagrangian is

$$(1)\quad L = \sum_j \mathbf{p}\mathbf{y}^j - \sum_j \alpha^j f^j(\mathbf{y}^j, z^j) - \mu\left(\sum_j z^j - Z^*\right).$$

As usual, $\mathbf{p}$ represents the price vector ($1 \times N$), and the α^j's and μ are appropriate Lagrange multipliers.

Assuming that the implicit production functions are concave and that all constraints are binding, the following first-order conditions describe the optimal choice of production activities.

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(2) $p_n - \alpha^j f_n^{\,j} = 0$ for all j, n, and

(3) $-\mu - \alpha^j f_z^{\,j} = 0$ for all j.

Subscripts on functionals denote partial derivatives and those on vectors denote particular vector elements.

Because only z is an externality quantity, profit maximization by firms will satisfy equation (2) but not (3). To also attain (3), firms theoretically would be confronted with an economic incentive for reducing emissions. Let s represent the per unit incentive on pollutant emissions. This incentive will be a charge at the margin (the externality is detrimental) but can be either a net charge or subsidy to each firm. For this generalization, let Z represent the incentive base level, a predetermined quantity from which greater emissions are charged at rate s and lesser emissions are subsidized at the same rate. Z bears no necessary relationship to Z^* and must be independent of actual emissions. If firm j maximizes profits in the presence of such an incentive, then its Lagrangian is

(4) $L^j = \mathbf{p}\mathbf{y}^j + s(Z - z^j) - \delta^j f^j(\mathbf{y}^j, z^j).$

Optimality conditions are then given by equations (5) and (6):

(5) $p_n - \delta^j f_n^{\,j} = 0$ for all n.

(6) $-s - \delta^j f_z^{\,j} = 0.$

Therefore, referring to (3) and (6), if the private value of productive abilities is equivalent to the social value ($\delta^j = \alpha^j$) and the incentive is chosen to equal μ, then the social and private solutions are the same. The first of these conditions is satisfied, but the second can be a major problem. The prescribed method for attaining $s = \mu$ is a trial-and-error procedure in which s is established at some initial level and iteratively adjusted until the standard, Z^*, is just reached. While it is easy to design a mechanism which converges s to μ, the speed of this convergence is very much in doubt. This issue, although important, is not discussed here.

The optimal incentive, s^*, is the same for all firms and is dependent upon the incentive base level. Use of this concept generalizes the model by incorporating the entire charge-subsidy spectrum. A pure charge exists if Z is equal to zero. Choosing each firm's previous externality generalization for Z corresponds to a pure subsidy. The specification employed here recognizes choices lying between these two extremes and permits control over equity and efficiency in externality resolution. Z can be interpreted as an initial endowment which the firm can then sell (collect a subsidy on) or buy more of (pay a charge for).

This analysis is neutral with respect to whether chosen economic incentives are subsidies or charges. The literature on this matter posits asymmetry between subsidies and charges. Subsidies will preserve marginal enterprises and may even induce entry by firms which were previously unprofitable (Baumol and Oates). Charges will do the opposite. Thus, there will be more polluters under subsidies than charges. Moreover, the incentive required with a subsidy will be slightly higher than with a charge achieving the same abatement level. Nonetheless, either policy will be least-cost in a strict sense. The difference is distributional and related to a type of income effect involving entry and exit by firms.

An equally efficient set of regulations can be mathematically stated using profit functions. Firm j's (optimal) profit function, $\pi^j(\mathbf{p}, s)$, specifies optimal profits as a function of the price vector and the incentive level. That is,

$$\pi^j(\mathbf{p}, s) = \text{Max } \mathbf{p}\mathbf{y}^j + s(Z - z^j)$$
$$\text{subject to } f^j(\mathbf{y}^j, z^j) = 0.$$

Given previous assumptions, we need only disallow constant returns to scale in order to guarantee the existence of $\pi^j(\mathbf{p}, s)$. Applying Hotelling's lemma (Varian), the firm's optimal output of pollution is the derivative of the profit function with respect to the cost of emitting the pollutant. Evaluating this partial derivative at the appropriate prices and the optimal incentive, we have an equally optimal regulation for firm j.

(7) $z^{j*} = z^j(\mathbf{p}, s^*) = \left.\dfrac{\partial \pi^j(\mathbf{p}, s)}{\partial s}\right|_{\mathbf{p}, s^*}$ for each j.

Equation (7) describes a set of optimal regulations which, when enforced, will achieve the targeted emission restriction at least cost. Allocatively, the regulations defined by equation (7) are as efficient as the least-cost incentive, $s^* = \mu$. Each of the policies is the dual of the other. This dual relationship guarantees that the allocative efficiency of both programs is equal. The typical argument favoring incentives over regulations is based on informational efficiency. Equation (7) clarifies this issue by indicating that profit functions must be known in order to calculate optimal regulations. Profit functions require knowledge of each firm's implicit production function. Hence, the information needed to determine least-cost regulations is greater than that for least-cost incentives.

Therefore, the point externality can be approached with either of two policies; the first is price guided (an incentive), and the second is quantity guided (regulations). Monitoring and assessment of the incentive or monitoring and enforcement of the regulations will lead to the desired result—least-cost achievement of the aggregate restriction on point-source emissions. Unfortunately, monitoring of nonpoint pollutants is either infeasible or impractical. Hence, the two policies specified above are unworkable because each requires that the pollutant be monitorable.The next section illustrates how some theoretical adjustments can reestablish the usefulness of these approaches.

A Nonpoint Externality

Externality levels have often been linked directly to an output quantity. In such cases, least-cost incentive or regulatory policies can be attached to the output quantity rather than the actual amount of externality. Meade was the first to extend these output-oriented policies to inputs by postulating that externality levels may be dependent on the amount of productive factors employed. Under these conditions, incentive and/or regulatory policies may be applied individually to every factor on which externality generation depends. Of course, the choice of incentives and regulations must all be correct in order to induce least-cost responses by firms.

Whereas it would be technically difficult and prohibitively expensive to measure nonpoint pollutant emissions by individual firms, factors influencing those emissions can be measured at a more reasonable cost. The refinements undertaken below to expand the point externality model so that it accounts for these possibilities are, therefore, valuable. This is true despite the fact that there are many unresolved problems regarding the precise linkages between management choices (and physical land characteristics) and the generation of agricultural runoff. The amended model is completely general because it accommodates a functional relationship between externality levels and outputs, inputs, or some combination of the two.

Assume that every firm is fully utilizing its productive abilities, i.e., $f^j(\mathbf{y}^j, z^j) = 0$ for all j. Applying the implicit function theorem, we have that there exists a neighborhood about $\mathbf{y}^j$ and smooth functions g^j such that $f^j[\mathbf{y}^j, g^j(\mathbf{y}^j)] = 0$ for all j throughout the neighborhood. The only restrictive assumption necessary to apply this theorem requires that $f_z^j \neq 0$. In the presence of the unabated externality, each farm chooses $f_z^j = 0$, so the theorem does not apply. However, externality policy is intended to direct the farm away from this point, so we know that this assumption is indeed valid.

The implication of this theorem is that externality production is expressible as a continuously differentiable function of all inputs and outputs. Hence, this formulation is completely general, accommodating input and/or output determinants of the nonpoint externality. For convenience, assume that the nonpoint production function, $g^j(\mathbf{y}^j)$, does not differ among farms. Hence, the superscript on this function is dropped but may be reinserted with little change in the analysis. This assumption does not imply, for example, that all farms have the same soil types and slopes; these variables are arguments of g.

Use of this functional relationship suggests four distinct policies.[1] The first, a nonpoint incentive, is equivalent to the incentive formulation of the previous section and shall continue to be denoted as s^*. While this incentive is unchanged, policy operation must be revised. Instead of monitoring pollutant emissions, the individual determinants of these emissions are monitored, and the nonpoint production function is used to calculate z^j for each farm. Not every farm input and output needs to be monitored; most will be unrelated to pollution generation and will not enter into g. Under these conditions, farm profits are $\mathbf{p}\mathbf{y}^j + s[Z - g(\mathbf{y}^j)]$.

The second policy, a least-cost system of nonpoint standards, is still expressed by equation (7). Enforcement requires that farm production activities be monitored in order to estimate actual emissions using $g(\mathbf{y}^j)$.

Third, the nonpoint production function can be used to determine individual management incentives for each production activity affecting emissions. Properly chosen, these incentives can induce least-cost efficiency. Let $\boldsymbol{\sigma}$ denote the vector of incentives attached to the elements of $\mathbf{y}_j$. Thus, σ_n is the incentive (either a marginal charge or subsidy) on activity y_n. Letting $\mathbf{Y}$ represent the vector of management incentive base levels (one for each activity), farm profits are $\mathbf{p}\mathbf{y}_j + \boldsymbol{\sigma}(\mathbf{Y} - \mathbf{y}_j)$. Analogous to Z above, each Y_n is a predetermined and arbitrary quantity from which greater activity levels are charged and lesser activity levels are subsidized at the rate σ_n (vice versa if σ_n is negative). Maximizing profits subject to the newly stated technological constraint for each farm yields the following Lagrangian and optimality conditions.

$$(8)\quad L^j = \mathbf{p}\mathbf{y}^j + \boldsymbol{\sigma}(\mathbf{Y} - \mathbf{y}_j) - \delta^j f^j[\mathbf{y}^j, g(\mathbf{y}^j)]$$
$$p_n - \sigma_n - \delta^j(f_n^j + f_z^j g_n) = 0 \qquad \text{for all } n, j.$$

Society's problem is slightly altered because of the removal of z^j as an independent variable. The social Lagrangian and least-cost efficiency are specified by the following relations.

$$(9)\quad L = \sum_j \mathbf{p}\mathbf{y}^j - \sum_j \alpha^j f^j[\mathbf{y}^j, g(\mathbf{y}^j)] - \mu\left[\sum_j g(\mathbf{y}^j) - Z^*\right]$$
$$p_n - \mu g_n - \alpha^j(f_n^j + f_z^j g_n) = 0 \qquad \text{for all } n, j.$$

Comparison of (8) and (9) identifies the least-cost management incentives as

$$(10)\qquad \sigma^*_n = \mu g_n = s^* g_n \qquad \text{for all } n.$$

This system of incentives is not necessarily the same for all farms because derivatives of the nonpoint production function are evaluated at different

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[1] Much information would be needed to specify precisely a nonpoint production function. To identify accurately the relevant physical relationships, a simulation model may be needed. Hence, the theoretical function may be very complex in actual application. Although the validity of nonpoint production functions must be examined in each setting, their theoretical consequences are significant since they imply interesting and useful policy and research conclusions.

activity levels. Note that each management incentive σ^*_n is a marginal charge or subsidy depending on whether g_n is positive or negative, respectively. It is expected that g_n is zero for many activities.

For a fourth and final runoff policy, there is a system of standards which is the dual to management incentives. Letting $\pi^j(\mathbf{p}, \boldsymbol{\sigma})$ denote the farm's profit function in the presence of management incentives, Hotelling's lemma can be used to specify regulatory constraints on individual farming activities. These constraints are management practices, and are defined by equation (11).

$$(11) \quad y_n^{j*} = y_n^j(\mathbf{p}, \boldsymbol{\sigma}^*) = \left| \frac{\partial \pi^j(\mathbf{p}, \boldsymbol{\sigma})}{\partial \sigma_n} \right|_{\mathbf{p}, \boldsymbol{\sigma}^*} \quad \text{for all } n, j.$$

The absolute-value operator has been added because the derivative of the profit function with respect to an input price results in the optimal supply of the input (which is negative). This slate of management practices will induce the least-cost achievement of the environmental goal. There is, of course, no need to monitor activities for which $g_n = 0$.

Nonpoint Policy

The four policy alternatives for nonpoint pollution are importantly related to one another. With the usual caveats concerning the omission of income effects, transaction costs, and time, every one of these policies induces the allocatively efficient achievement of the target objective. Least-cost parameters for each of these policies are summarized in table 1.

Even though all four policies are allocatively efficient, they differ in many respects. First is the number of parameters to be specified by the controlling authority. There are, at most, one nonpoint incentive, J nonpoint standards, $N \times J$ management incentives, and $N \times J$ management practices needed to accomplish the objective at least cost. In order for the least-cost goal to be attained in two of these programs, the nonpoint incentive and nonpoint standards, individual farmers must have information on the nonpoint production function and its use. Otherwise, they will not be able to choose production plans to maximize profits. If dissemination of this information is a problem, there is justification for pursuing one of the two management policies.

Another major difference among these programs relates to the amount of policy transaction costs that each policy will incur. Policy transaction costs include the costs of initial information for a specific instance of market failure and of deciding whether or not to invoke a nonmarket allocation mechanism, the costs of policy design, the structural costs of the administering agency, variable enforcement costs (for monitoring, assessment, and litigation), and the costs of periodic policy reevaluation. Just as transaction costs are incurred for the operation of markets, the implementation and management of public policies also involve transaction costs. While many of these costs are the same for alternative policies, some of the variable enforcement costs will be different. These differences can become very important for policy selection when the administering agency has a limited budget.

Table 1. Efficient Nonpoint Policy Parameters

Incentives	Regulations	Type
$s^* = \mu$	$z^{j*} = \left.\frac{\partial \pi^j(\mathbf{p}, s)}{\partial s}\right\|_{\mathbf{p}, s^*}$ for each j	Nonpoint Incentives or Standards
$\sigma^*_n = s^* g_n$ for each j and n	$y_n^{j*} = \left\|\frac{\partial \pi^j(\mathbf{p}, \boldsymbol{\sigma})}{\partial \sigma_n}\right\|_{\mathbf{p}, \boldsymbol{\sigma}^*}$ for each j and n	Management Incentives or Practices

Other differences include the distribution of costs and the ability of each policy to respond to price changes, technological innovation, and entry/exit. Policy adoption is heavily influenced by the distribution of costs between farmers and government as well as among farmers themselves (Sharp and Bromley). In the generalized format of the preceding model the equity of each incentive program is highly variable. The two incentives programs can result in either net charges or net subsidies for farmers depending on the initial choice of incentive base levels (Z or $\mathbf{Y}$). The regulatory policies also are flexible because varying amounts of lump-sum transfers and cost sharing can be engaged.

Implications for Economic Research

A basic tenet of natural resource economics is that both costs and benefits of public investment or intervention should be jointly assessed before the selection of a particular action. Within least-cost (cost-effective) frameworks for pollution control, benefits are improved environmental quality. Therefore, policy selection requires that environmental effectiveness as well as economic impact be known to decision makers. Published research has concentrated on likely economic impacts (i.e., costs) of various actual or proposed nonpoint policies. This kind of research needs to be complemented with analysis involving nonpoint production functions.

It is also important that each nonpoint policy under consideration be specified so that it is a least-cost means of obtaining a given level of environmental improvement. Often this has not been accomplished (Griffin and Bromley). Therefore, policy costs have been overstated. The policy parameters in table 1 can serve as a guide for improved research. Equations (10) and (11) demonstrate that neither management practices nor management incentives can be economically efficient if they are not specified using the appropriate nonpoint production function(s).[2] The correct application of this information will result in the identification of an optimal set of management practices or incentives. Single management practices or incentives will be economically inefficient.

Other implications for economic research are provided by the dualistic relation between least-cost incentives and least-cost regulations. Recognition of this relationship leads to some important conclusions. First, least-cost efficiency can be achieved with regulations. However, such regulations (either nonpoint standards or management practices) will be different for each farm. These differences are apparent in table 1. Therefore, when regulations are constrained to be equal for all farms or for all farms in each land class, incentive programs will be more efficient. Equity concerns and political realities make equivalent regulations more likely. Under these circumstances incentives will be less costly than regulations achieving the same amount of nonpoint emissions (neglecting policy transaction costs). However, this advantage will be concealed by economic models of agricultural pollution unless they properly reflect the differing productive abilities and resource constraints of individual farms (Jacobs and Casler). Since national and regional models are usually based on land classes and soil types rather than individual farms, this problem does exist.

The dualism between regulations and incentives provides insight in designing least-cost parameters for any of the four fundamental policy types. Assuming that we have an appropriate profit-maximization model incorporating several or many farms and a constraint on total emissions, the optimal nonpoint incentive is the shadow price of the environmental constraint; optimal nonpoint standards are the emissions of each farm; and optimal management practices are the activities undertaken by each farm in the solution to this problem. Only the management incentives require additional calculations. The partial derivatives of the nonpoint production function must be evaluated, and the management incentives must be established according to equation (10). Nonpoint externality theory identifies four policy types. Within the context of this theory, all four policies are equally efficient. However, these policies are not equivalent in equity, policy transaction costs, and political and public acceptability. Therefore, the existence of four distinct policies for nonpoint problems expands the number of opportunities for actual programs.

The flexibility provided by incentive base levels also improves program options. In the theory developed here, the equity of incentive programs becomes a policy parameter. Therefore, if it is found that one of the two incentive policies offers an important opportunity for the efficient achievement of an environmental goal, then that policy need not be dismissed because it is judged to be inequitable.

Conclusions

The nonpoint character of agricultural runoff renders traditional pollution policies inoperative because these policies must identify the externality contributions of each economic agent. This fact has increased the difficulty of economically analyzing alternative runoff policies. It also may have led to the institution of policies without sufficient attention to their economic consequences.

Economic guidance for nonpoint policy can be obtained by relying upon nonpoint production functions. These functional relationships permit the amount of pollution in the runoff of individual farms to be estimated when their respective production activities are known. The essential feature of a nonpoint production function is that it allows economically efficient policies to be based upon those factors which determine pollution rather than the pollutant itself.

The following statements summarize the major consequences of omitting the nonpoint production function from any economic analysis of agricultural pollution. First, only the costs of prospective policies can be identified. Because the linkage between production activities and nonpoint pollution is not explicitly included in the analysis, it will be impossible to identify policy benefits. Second, because any two policies will differ environmentally as well as economically, no conclusions are possible regarding the relative merits of alternative programs. Third, it will be impossible to calculate a set of management practices or management incentives which are truly "best" in terms of the costs of achieving any given level of pollution abatement. Fourth, nonpoint incentives and nonpoint standards are not realistic policy alternatives because emissions cannot be monitored or estimated.

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[2] The universal soil loss equation (USLE) is a nonpoint production function. It is a simple relationship expressing soil loss as a multiplicative function of physical and management parameters. While the USLE actually measures erosion not runoff, some studies using it have achieved limited success in identifying economic and environmental effects of various policies.

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